

University of Groningen

Impacts of biogas production on nitrogen flows on Dutch dairy system

Hoang, Dieu Linh; Davis, Chris; Moll, Henri C.; Nonhebel, Sanderine

Published in:
Journal of Industrial Ecology

DOI:
[10.1111/jiec.12956](https://doi.org/10.1111/jiec.12956)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2020

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Hoang, D. L., Davis, C., Moll, H. C., & Nonhebel, S. (2020). Impacts of biogas production on nitrogen flows on Dutch dairy system: Multiple level assessment of nitrogen indicators within the biogas production chain. *Journal of Industrial Ecology*, 24(3), 665-680. <https://doi.org/10.1111/jiec.12956>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

RESEARCH AND ANALYSIS

Impacts of biogas production on nitrogen flows on Dutch dairy system

Multiple level assessment of nitrogen indicators within the biogas production chain

Dieu Linh Hoang¹  | Chris Davis² | Henri C. Moll¹ | Sanderine Nonhebel¹

¹Center for Energy and Environmental Sciences, University of Groningen, Groningen, Netherlands

²Invenia Labs, Cambridge, UK

Correspondence

Dieu Linh Hoang, University of Groningen—Center for Energy and Environmental Sciences, IVEM, Nijenborgh 6, Groningen 9747 AG, Netherlands.
Email: d.l.hoang@rug.nl

Editor Managing Review: Ester van der Voet

Funding information

NWO - Nederlandse Organisatie voor Wetenschappelijk Onderzoek (Dutch Organisation for Scientific Research), Grant/Award Number: 428-15-519 of TKI-Logistiek

Abstract

Biogas production on dairy farms is promoted as a climate change measure since it captures methane, a greenhouse gas emitted by manure, and produces renewable energy. Digestate is a by-product of biogas production and is often used for nutrient recycling in a similar way as traditional manure. Despite having similar functions, manure and digestate have different behaviors related to nitrogen recycling and nitrogen emissions which are significant agricultural and environmental concerns of manure. This paper provides an insight into the impact of biogas production on nitrogen emissions and nitrogen recycling issues of the current dairy farming practice. Using the Substance Flow Analysis (SFA) approach, we analyzed the changes on three levels: manure handling, dairy farm, and the whole chain. Four biogas production options on a Dutch dairy farm related to types and sources of feedstocks were considered. We quantified biogas output, nitrogen fertilizer replacement percentage (%) and consequential nitrogen emissions (kgN/year; kgN/m³ biogas produced) of these productions in comparison with the baseline of current dairy farming without biogas. We conclude that biogas production options with additional feedstocks will cause profound changes in the nitrogen recycling on dairy farms and the nitrogen emissions at the chain level. Besides, the results show that determining the optimal biogas production option can be challenging as the evaluation is highly dependent on the used nitrogen indicator and the included level of analysis. Our findings show how SFA and a multilevel perspective can give a broader understanding of environmental trade-offs.

KEYWORDS

codigestion, dairy biogas, multiple level assessment, nitrogen emissions, nitrogen recycling, substance flow analysis (SFA)

1 | INTRODUCTION

Biogas production with an anaerobic digestion approach captures methane (CH₄) from manure as a source of energy which would otherwise be an emission (Burton & Turner, 2003). For its benefits in both eliminating greenhouse gas emissions and replacing fossil fuels, biogas plays an important role in climate change reduction programs (Velten, Donat, Andrew, Prah, & Wevers, 2014). While biogas production reduces methane emissions, it can bring up the trade-offs with regard to the nitrogen issues of the dairy farms.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2019 The Authors. *Journal of Industrial Ecology*, published by Wiley Periodicals, Inc., on behalf of Yale University

Nitrogen is the primary and the largest nutrient that is required for plant growth (Ohyama, 2010) but it is also involved in several types of emissions (NH_3 , NO_x , N_2O , NO_3^-) on the dairy farms. These emissions result in various impacts such as climate change, ozone depletion, air pollution, and eutrophication (Fields, 2004; Leip et al., 2015).

Since manure has a low biogas yield, it can be codigested with different types of feedstock to increase the biogas output (Deublein & Seteinhauser, 2008). This codigestion practice means that additional nitrogen might be brought up to the existing nitrogen flow of the dairy farming system.

Digestate is an inevitable and substantial by-product of biogas production. Instead of being disposed as waste, it is proposed to replace manure (Lukehurst, Frost, & Al Seadi, 2010) which has been traditionally recycled for nutrients in agriculture (Sims & Maguire, 2005). Massively adopting biogas production on dairy farms will result in a large-scale replacement of manure by digestate.

These expected trends pose the question what are the nitrogen-related environmental impacts of producing and replacing manure by digestate on the dairy farming system.

To study the environmental impacts of biogas production, Life-Cycle Assessment (LCA) is mostly used (Afrane & Ntiamoah, 2011; Hijazi, Munro, Zerhusen, & Effenberger, 2016; Ramírez-Arpide et al., 2018; Stucki, Jungbluth, & Leuenberger, 2011). Though most studies agree that biogas production is a better way for reducing GHG emissions in comparison with other ways of handling manure, they also point out that it increases nitrogen emissions and nitrogen-related eutrophication (Paolini et al., 2018). Tiwary, Williams, Pant, and Kishore (2015) also mentioned that more research is required on the environmental impact of codigesting different feedstocks, particularly the impact on nitrogen compounds. Digestate and crop production are identified as significant contributors to nitrogen emissions (Bacenetti, Sala, Fusi, & Fiala, 2016). Another study shows that codigestion causes a larger amount of nitrogen to flow into the production system (Pehme, Veromann, & Hamelin, 2017). The impact of codigesting grass was assessed and found to increase eutrophication by 2–10 times compared to mono-digestion of manure. This indicates that the impact on nitrogen could be a serious problem and requires more attention.

Although LCA studies show the gravity of the impact, it is also important to know how biogas production affects local nitrogen impacts in relation to local regulations. In the Netherlands, the farm level is the target of national regulations on nitrogen for artificial fertilizer and manure. These regulations are due to critical environmental impacts of their emissions in the form of nitrate (NO_3^-)—often seen through leaching and runoff. To prevent supplying more nitrogen than the crops need and to reach an acceptable leaching level, Dutch regulations standardizes the maximum allowable amount of nitrogen applied per hectare. This allowance is based on the amount of cultivated land, soil types, and crop types (RVO 2018a; Schröder & Neeteson, 2008; Van Grinsven, Tiktak, & Rougoor, 2016). Since decisions on making biogas and recycling manure or digestate are made at the farm level, the impact on nitrogen flows also needs to be quantified for the farm. On the other hand, when talking about the use of digestate, LCA study make the simple assumption that digestate can replace a certain amount of artificial fertilizer. However, each farm only has a certain need of artificial fertilizer while LCA only focuses on the whole supply chain and neglects the need of each particular farm. So, while LCA studies give a good overview of the impact of the broader production chain, it is not suitable for such local implications.

To gain insights on the change in nitrogen-related environmental impact on the Dutch dairy farming system, it is important to understand the change in its nitrogen flows. This makes SFA a more suitable methodology. By modelling nitrogen as a single substance, it is possible to model the impact on nitrogen of different biogas configurations at specific system levels such as the farm or the production chain. This also gives a greater insight into nitrogen recycling on both of these levels, because mass balancing in SFA guarantees that all nitrogen has to be accounted for. Nitrogen flows of agricultural production chains have been well studied but rarely include biogas production within the system (Chatzimpiros & Barles, 2013; Daatselaar, Reijs, Oenema, Doornewaard, & Aarts, 2015; Schröder, 2009). In the field of energy, nitrogen flows have been studied at biogas plant level (Möller, Schulz, & Müller, 2010) but not at the whole supply chain level.

2 | RESEARCH QUESTIONS

The previous section shows the emergence of nitrogen-related emissions of biogas production and the influence of the local regulatory context on the nitrogen recycling at Dutch dairy farms. We identified the first knowledge gap in understanding the impact of changing nitrogen flows at the dairy farms and the whole biogas production chain. The second knowledge gap is the lack of SFA studies on nitrogen flows of the biogas production chain which can help to fill the earlier gap. We assume that the change in nitrogen-related environmental impact is corresponding to the change in the nitrogen flows.

This paper will apply SFA to examine the impact of biogas production on the emissions and nitrogen recycling of the current dairy farming practice. Two analytical levels are included: dairy farm level and supply chain level. Our research questions are as follows:

- How do biogas production options change *nitrogen emissions* of the current Dutch dairy farming system at the two mentioned levels?
- How do biogas production options change *nitrogen recycling capacity* of the current Dutch dairy farming system at the two mentioned levels?
- Which biogas production option(s) provide more biogas with less trade-off with regard to the nitrogen flows?

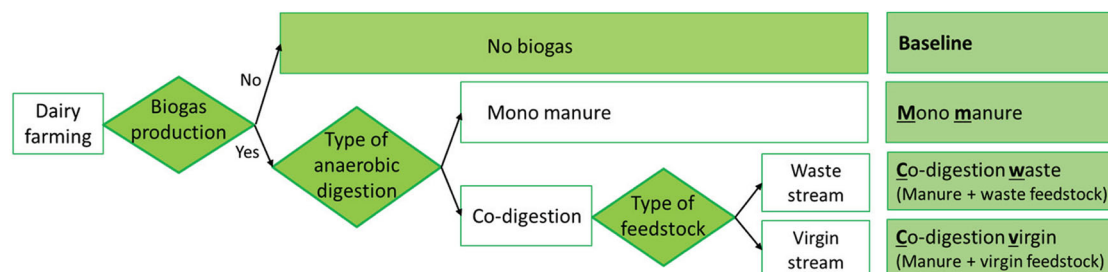


FIGURE 1 Biogas production options on a dairy farm

3 | METHODOLOGY

3.1 | Static SFA

SFA is a well-established methodology to model the flow of a single substance within a system defined in space and time (Brunner & Rechberger, 2011). In static SFA, the model is composed by linear equations which describe the relation between the nodes and flows. Nodes are processes and flows are the actual substance amounts that get in or get out of a process. Static SFA is suitable to answer our research question because we are interested in a single substance flow—the nitrogen—in specific spatial boundaries. We are only concerned with the magnitude of change of the flow itself rather than the molecules which cause environmental impacts. In this research, to build up the model, we did these steps following the instruction of the SFA approach (van der Voet, 2002):

- Step 1: Identify the most common biogas production options on a dairy farm
- Step 2: Set the system boundaries, processes, and nitrogen flows included in each biogas production option
- Step 3: Quantify the nitrogen flows of all biogas production options
- Step 4: Use indicators to compare the nitrogen flows between biogas production options

3.2 | Biogas production options

Based on the involvement of biogas feedstock, there are two typical types of anaerobic digestion on dairy farms: mono-digestion of manure and codigestion of a mixture of manure and another feedstock (Tufaner & Avşar, 2016). To take into account the environmental costs of producing feedstock for codigestion, we included the origin of the additional feedstocks. The additional feedstock is from either a waste stream or a virgin crop dedicated for biogas production. To make them comparable, the two types of feedstock are assumed to have the same characteristics and the waste feedstock is also plant-based. As a result, four biogas production options are considered in this study (Figure 1).

3.3 | System description

In this section we define which processes and nitrogen flows are included in our calculation corresponding to levels of analysis and how they are different in each biogas production option. This is based on descriptions of dairy production, crop production and biogas production from existing research such as Schröder (2009) and de Vries, Vinken, Hamelin, and de Boer (2012). As mentioned above, this research aims to understand the nitrogen flows and their changes caused by biogas production at the dairy farm level and at the supply chain level. To compare the switch from traditional manure storage to anaerobic digestion, we also add the manure handling level in our analysis.

Details of processes and nitrogen flows of four biogas production options in different analytical levels are visualized in Figure 2.

3.3.1 | Manure handling level

- **Baseline:** *Manure storage* is the only one process included in this analytical level. *Nitrogen (N) in manure excreted* is the inflow; *N in manure after storage* and *N emissions during storage* are the outflows. (See Table 1 for a listing and explanation of all major abbreviations used in this article.)
- **Mono Manure:** Two processes are included: *anaerobic digestion (AD)* and *digestate storage*. AD is also the *biogas production* or *energy production* process. AD has *N in manure excreted* as the inflow, *biogas* (without N) and *N in digestate* as the outflows. *N in digestate* is the inflow of *digestate storage*. *N in digestate after storage* and *N emissions during storage* are the outflows of this process. The AD process happens before digestate storage. This is to avoid fresh manure reducing its energy content as time passes and to store the digestate (digested manure) before field applications (Rosenberg & Kornelius, 2017).

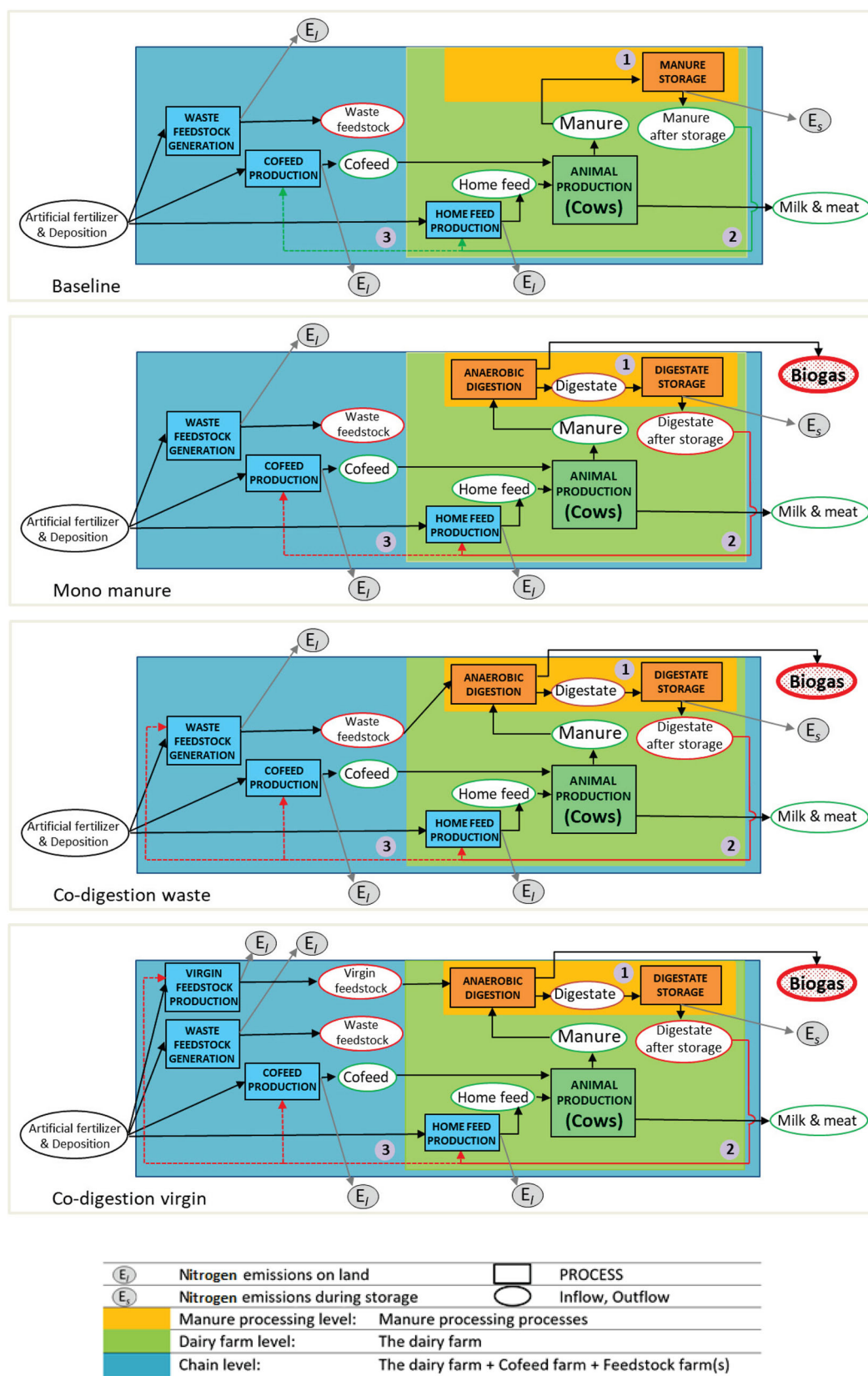


FIGURE 2 Nitrogen flows of biogas production options under three analytical levels

TABLE 1 List of abbreviations

Abbreviation	Explanation
AD	Anaerobic digestion
CNE	Consequential Nitrogen Emissions
N	Nitrogen
LCA	Life Cycle Assessment
NFA	Nitrogen artificial Fertilizer Actually used
NFD	virgin Nitrogen artificial Fertilizer Demand
NFRV	Nitrogen Fertilizer Replacement Value
NFRP	Nitrogen Fertilizer Replacement Percentage
SFA	Substance Flow Analysis

- *Codigestion Waste and Codigestion Virgin*: These two options are quite similar to Mono Manure with two processes of AD and *digestate storage* and their flows. However, the flow *N in additional feedstock* from waste or virgin crop, respectively, is added as the second inflows of the AD process of each option.

3.3.2 | Dairy farm level

The dairy farm level covers the manure handling level. Except manure handling processes, other processes on dairy farm are similar in all biogas production options. They are *animal production* and *home feed production*. Animal production has *N in home feed* and *N in cofeed* as inflows; *N in animal products* (meat and milk) and *N in manure excreted* as outflows. Home feed is the feed for cows grown in dairy farm which is often grass and silage maize. Cofeed is extra feed for cows which is mostly plant-based and obtained from outside of the dairy farms. Examples for cofeed are beet roots, brewer's grain. Inflows of *home feed production* is *N in deposition*, *N in artificial fertilizer* and *N in nutrient recycling flows*. Nitrogen deposition consists of several natural processes which provide reactive nitrogen from the atmosphere to plants both as gases and in precipitation (Air Pollution Information System, 2016). Corresponding to each biogas production option, the *nutrient recycling flows* are *manure after storage* and/or *digestate after storage*. Outflows of *home feed production* are *N in emissions on land* which is contributed by all inflows (see Section 3.4) and *N in home feed* harvested.

3.3.3 | Supply chain level

The supply chain level considers the whole supply chain system of biogas production which includes the dairy farm (thus includes the manure handling) and other farms that may produce inputs for the dairy farm. Cofeed farms are represented by a single *cofeed production* process which includes the cultivation of different crop types. For simplification, N flows and losses in processes between cultivation and the dairy farm are not included. Similarly, additional biogas feedstock sources are defined as two crop production processes: *virgin feedstock production* and *waste feedstock generation*.

In all biogas production options, the supply chain level includes processes and flows on the dairy farm, *cofeed production* and *waste feedstock generation*. *Cofeed production* is required for dairy farming no matter if biogas production happens or not. *Waste feedstock generation* exists regardless whether the waste is used for biogas production or not; we add this compartment to all production options to ensure the comparability of the supply chain level analysis. *Manure after storage* and *digestate after storage* after fulfilling the nitrogen demand of the dairy farm also recycled on the farms where its N is originated from cofeed farm and corresponding feedstock farm. In the option Codigestion Virgin, the supply chain level includes extra production of virgin feedstock. Home feed production, cofeed production, Inflows and outflows of crop production are similar, only different in type of crop harvested.

Our study excludes nitrogen flows from these processes:

- *Artificial fertilizer production*: this is one of the first processes of the biogas supply chain which transforms nitrogen in the air into reactive nitrogen that can be used by plants. There are insignificant nitrogen losses in this process since the chemical industry aims to maximally retain the desired substances in the production flows (Blonk Consultant, 2012; European Fertilizer Manufacturers' Association, 2000a, 2000b; Kamphus, 2014). Because of this triviality the artificial fertilizer production process is excluded from our study.
- *Waste decomposition*: this process appears in all studied biogas production systems but is not affected by any nitrogen flows from the biogas production options. We exclude this because it does not differ between the studied systems.
- *Fuel combustion and transportation*: N_2O and NO_x are nitrogen emissions from these processes and often included in LCA studies. However, from an SFA perspective, we do not include them in our work because the nitrogen of these emissions does not come from the nitrogen in fertilizer and feedstocks.

TABLE 2 The Dutch dairy farm and nitrogen flows in animal production used in this research (Schröder, 2000, 2009; Wageningen University & Research, 2018)

			Per ha per year	Per dairy farm per year
Farm structure	Area	ha	1	55
	Dairy cows	head	1.56	86
	Calves > 1 year	head	0.52	29
	Calves < 1 year	head	0.65	36
Animal production	Inflows	Home feed	kgN	250
		Cofeed	kgN	131
	Outflows	Meat	kgN	12
		Milk	kgN	77
		Manure excreted	kgN	292

3.4 | Nitrogen flows quantification

In this section, we describe the quantification of nitrogen flows for the following processes based on the system description identified in Section 3.3 and inventory data from literature: animal production, energy production, manure handling, and crop productions. The unit of nitrogen flow is kgN/dairy farm/year. *Please note that the formulae presented in this paper are in a generalized form. Not all terms cited in a formula exist in all biogas production options. Missing terms have a default value of 0.*

3.4.1 | The standardized Dutch dairy farm and animal production

Production scale of the dairy farm defines the magnitude of the nitrogen flows of the whole biogas supply chain for the following reasons:

- The level of dairy production and the number of cows decides how much feed is required and how much manure is produced.
- The size of the farm determines how much home feed can be grown, thus how much fertilizer is required by the dairy farm and how much cofeed is imported.
- The amount of manure produced limits how much additional feedstock can be used for biogas production on the dairy farm, and thus the biogas output.

The most extensive data of nitrogen flows on Dutch dairy farm is from Schröder (2009) and Schröder (2000). For our calculation, we used these sets of Schröder as the core of our model and adapt other data to fit with it.

To make this data set usable in our SFA model, Schröder's numbers needs to be converted from kgN/ha/year unit to kgN/dairy farm/year unit by multiplication with the number of ha per dairy farm. Based on the latest data available on average Dutch dairy farm size in Wageningen University & Research (2018), we took 55 ha as the standardized area of the dairy farm in our calculation. Numbers of the dairy farm and nitrogen flows in animal production used in this research are described in Table 2.

3.4.2 | Energy production

According to Schröder (2009), each cow produces around 9,200 kg milk per year. We used this number of milk yield to look for mass of manure excreted per cow per year which were stated in RVO recent report of dairy manure production (RVO, 2018b). Assuming all excreted manure is collected for biogas production and multiplying the manure excreted per cows by the number of cows, we have 3,320 tons¹ fresh liquid manure as the annual manure production of the dairy farm.

In codigestion options, we used 50:50 mass-based as the feedstock mixing ratio which represents the typical practice of codigestion in Dutch dairy farms. This is because only codigestion projects with at least 50% feedstock from manure are subsidized and farmers want to maximize the amount of other feedstock for higher biogas output (Dumont, 2012; RVO, 2018c). As a result, the mass of the additional feedstock for each codigestion option is equal to the mass of manure excreted.

We chose the commonly used silage maize (Gebrezgabher, Meuwissen, & Oude Lansink, 2010) as the virgin feedstock. The waste feedstock has the same nitrogen content and biogas yield as silage maize. According to Centraal Veevoederbureau (2016), silage maize has a dry matter (DM) content and a nitrogen content of 301 g/kg and 14.4 g N/kg DM, respectively. Multiplying these two numbers with 3320 tons of silage maize required,

¹ The unit "ton" used in this paper is "metric ton."

TABLE 3 Biogas yield and nitrogen content of different biogas feedstocks used in this research

Type of feedstock	Category	Risk of pathogens & contaminations	Millions ton DM per year in NL	Biogas yield (m ³ /ton FM)	Potential biogas production (BCM biogas/year)	% of current gas demand in NL	N content (gN/kgFM)
Sludge from WWTPs	waste	high	0.33	504	0.44	0.66%	63.0
Household organic waste	waste	medium	0.58	160	0.47	0.71%	12.6
Roadside grass	waste	low	0.24	136	0.10	0.16%	11.3
Natural grass	waste	low	0.35	136	0.15	0.23%	11.3
Champost	waste	low	0.55	90	0.55	0.83%	6.3
Poultry manure	waste	low	0.81	133	0.38	0.57%	13.2
Pig manure	waste	low	0.88	102	0.61	0.92%	5.7
Dairy manure (slurry)	waste	low	0.74	33	0.24	0.36%	4.8
Sugarbeet pulp (dried)	by-product	low	0.28	631	0.20	0.29%	12.2
Glycerol	by-product	low	NIA	580–1000	NA	NA	0.0
Maize grains	virgin crop	low	NA	622	NA	NA	10.6
Silage maize	virgin crop	low	NA	168	NA	NA	4.3

Note. Data for “Type of feedstock,” “Category,” “Risk of pathogens & contaminations,” and “Millions ton DM per year in NL” is taken from Quik, Mesman, and van der Grinten (2016).

Data for “Biogas yield” is taken from BOKU and KTBL (2010).

“Potential biogas production” is the product of “Millions ton DM per year in NL” and “Biogas yield” and “DM/FM” taken from BOKU and KTBL (2010).

“% of current gas demand in NL” is calculated by taking 60% as the average ratio of CH₄ to the amount of biogas produced BOKU and KTBL (2010) and 40 BCM natural gas as the current gas demand of the Netherlands (Meliksetian, 2018)

“N content” of Dairy manure is calculated based on Nitrogen excretion and Manure excretion used in this paper; N content of other feedstocks is calculated based on Centraal Veevoederbureau (2016), Pratt and Castellanos (1981), Alberola, Lichtfouse, Navarrete, Debaeke, & Souchère (2008), Wierzbowska, Sienkiewicz, Krzebietke, & Sternik (2016), and CCBT (2013).

Abbreviations: WWTPs, Waste Water Treatment Plants; NL, the Netherlands; BCM, Billion Cubic Meter; FM, Fresh Matter; NIA, No Information Available; NA, Not Applicable.

we have 14387 kgN/dairy farm/year as *N in virgin feedstock*. *N in waste feedstock* is also 14387 kgN/dairy farm/year because of our assumption on the similarity of the two feedstock types.

Biogas output is calculated in unit m³/dairy farm/year with the following general equation. Biogas yield of fresh dairy manure and feedstocks are listed in Table 3.

$$\text{Biogas output} = \text{Mass}_{\text{manure excreted}} \times \text{Biogas yield}_{\text{manure}} + \text{Mass}_{\text{additional feedstock}} \times \text{Biogas yield}_{\text{additional feedstock}}$$

3.4.3 | Manure handling

Nitrogen emissions of artificial fertilizer, manure and digestate

Nitrogen emissions occur in manure storage and the land application of fertilizer and its replacement such as manure and digestate during the crop production. The focus of our research is nitrogen lost in the form of emissions, therefore, indirect nitrogen emissions which happen after the direct emissions are excluded. Direct NH₃, NO_x, N₂O emissions are caused by inorganic form of nitrogen (N) in the substance (van Middelaar, 2014; Vonk et al., 2016). Direct NO₃[−] emissions or NO₃[−] leaching is caused by total N: part of the emissions happens immediately with inorganic N and the other part occurs by the mineralization of its organic N in later period (de Boer, 2017). NO₃[−] emission rate in one soil condition remains the same to all type of N inputs (Intergovernmental Panel on Climate Change, 2006).

According to (Velthof et al., 2012), 63.5% of N in manure excreted is in inorganic NH₄⁺ form. This ratio of inorganic N increases by 22% after anaerobic digestion (Sørensen & Møller, 2011; Bonten, Zwart, Rietra, Postma, & de Haas, 2014). While biogas has insignificant trace amounts of N (Deublein & Seteinhauser, 2008), total N in manure and total N in digestate can be assumed to be the same on a kg-N basis (Bonten et al., 2014). The increase of inorganic N in the digested manure leads to higher emissions of gaseous emissions during storage and on land application.

Data on emissions of manure and digestate from experiments are varied. For this research, we used data from van Middelaar (2014) who specified gaseous nitrogen emissions of manure based on its organic N and inorganic N. We calculated NH₃, NO_x, N₂O emissions of digestate based on

TABLE 4 Nitrogen emission factors of artificial fertilizer, manure and digestate used in this research (see Section 1b in Supporting Information S1)

	Artificial fertilizer	Manure	Digestate
%NH ₄ -N/total N in Storage:			
%	100	63.50	77.47
Emissions during storage (kgN in emissions /100kgN input before storage)			
NH ₃ -N	0	6.35	7.75
N ₂ O-N	0	0.10	0.12
NO _x -N	0	0.10	0.12
%NH ₄ -N/total N before Land application:			
%	100	60.95	75.52
Emissions on land application—Grassland (kgN in emissions /100kgN input before storage)			
NH ₃ -N	2.5	11.58	14.35
N ₂ O-N	1	0.30	0.30
NO _x -N	0.55	0.06	0.06
NO ₃ -N	36.20	36.20	36.20
Emissions on land application—Arable land (kgN in emissions /100kgN input before storage)			
NH ₃ -N	2.5	1.22	1.51
N ₂ O-N	1	1.3	1.3
NO _x -N	0.55	0.27	0.27
NO ₃ -N	36.20	36.20	36.20

this approach of van Middelaar and the change of inorganic N percentage after anaerobic digestion (see SI Section 1b). Besides, van Middelaar data also include NH₃, NO_x, N₂O emissions of commonly used artificial fertilizer (CAN—calcium ammonium nitrate, 5Ca(NO₃)₂•NH₄NO₃•10H₂O) that we also need for our SFA model. NO₃⁻ leaching factor is calculated with data from Schröder (2009) and it is 0.362 kg NO₃-N per kg total N input. Nitrogen emission factors of artificial fertilizer, manure and digestate used in this research are presented in Table 4.

Nutrient recycling flows

N in manure after storage and *N in digestate after storage* are the nutrients recycling flows corresponding to each biogas production options, which are calculated as follows:

$$N_{\text{nutrient recycling flow}} = (N_{\text{manure excreted}} + N_{\text{additional feedstock}}) \times (1 - \text{factor } N_{\text{emissions during storage}})$$

N emission factors of manure and digestate (NH₃, NO_x, N₂O) are in Table 4.

3.4.4 | Crop production

Nitrogen inputs for crop productions

There are four types of crop production in our SFA model: home feed production, cofeed production, waste feedstock generation, and virgin feedstock production. To simplify, we assume that the ratios between *N in harvested products* and *N in different inputs* are constant, regardless of the parts of plant and types of crop. We used the data set of home feed production from Schröder (2009) to define these ratios.

For the *baseline*, the production of 250 kgN in home feed requires three types of nitrogen inputs: 292 kgN in recycled manure, 129 kgN in artificial fertilizer and 51 kgN in deposition; 222 kgN was lost via emissions (Schröder, 2009).

For nitrogen inputs of crop production on other farms and in other biogas production options, the nitrogen recycling situations would not be guaranteed to be like the dairy farm on the baseline. Therefore, we first standardize the nitrogen inputs via *nitrogen deposition and virgin Nitrogen artificial Fertilizer Demand* (NFD). Based on the standardized NFD and *N in nutrient recycling flows*, we can calculate the *Nitrogen artificial Fertilizer Actually used* (NFA). Since nitrogen emission factors of manure, digestate, and artificial fertilizer are different, so 1 kgN in manure or digestate after storage does not replace the same amount of *N in artificial fertilizer*. We use *Nitrogen Fertilizer Replacement Value* (NFRV) to convert N supply by manure and digestate to the equivalent N artificial fertilizer.

Nitrogen deposition for each kgN in crop harvested is calculated by ratio between *N deposition of home feed production* and *N in home feed harvested*. Formulae for NFD, NFA, and NFRV are described as following:

Nitrogen artificial Fertilizer Demand (NDF) is calculated based on the mass balance rule:

$$N_{\text{deposition}} + N_{\text{NDF}} = N_{\text{crop harvested}} + N_{\text{deposition}} \times \text{factor } N_{\text{on land emissions of deposition}} + N_{\text{NDF}} \times \text{factor } N_{\text{on land emissions of fertilizer}}$$

Thus,

$$N_{\text{NDF}} = \frac{N_{\text{crop harvested}} + N_{\text{deposition}} \times \text{factor } N_{\text{on land emissions of deposition}} - N_{\text{deposition}}}{1 - \text{factor } N_{\text{on land emissions of fertilizer}}}$$

N emission factors of artificial fertilizer (NH_3 , NO_x , N_2O , NO_3^-) are in Table 4.

NFRV. In agriculture, for short-term, this value indicates “the amount of N fertilizer that can be replaced by the N manure” in the year of application. Only *inorganic N manure* is supplied to the crop production at the application year. In the long-term, this value can be referred as *Manure N efficiency* which expresses as the amount of N fertilizer that can be replaced by both *inorganic N manure* in the first year and organic N manure mineralized in the following year (Webb et al., 2010). We discussed that digestate provides more short-term nitrogen to crops in comparison with manure (see Introduction). However, the same amount of nitrogen at start, digestate contributes less nitrogen to crop productions than manure does in the long-term due to its more nitrogen loss in form of emissions. In this research, we use the *long-term NFRV* approach because the static model only considers the equilibrium state of the studied substance. Long-term NFRV of manure and digestate is calculated based on mass balance rule of static SFA:

$$(\text{Long-term}) \text{ NFRV manure} = \frac{1 - \text{factor } N_{\text{on land emissions of manure}}}{1 - \text{factor } N_{\text{on land emissions of artificial fertilizer}}}$$

$$(\text{Long-term}) \text{ NFRV digestate} = \frac{1 - \text{factor } N_{\text{on land emissions of digestate}}}{1 - \text{factor } N_{\text{on land emissions of artificial fertilizer}}}$$

Nitrogen artificial Fertilizer Actually used (NFA).

$$N_{\text{NFA}} = N_{\text{NDF}} - N_{\text{manure after storage}} \times \text{NFRV}_{\text{manure}} - N_{\text{digestate after storage}} \times \text{NFRV}_{\text{digestate}}$$

Nitrogen emissions of crop productions

Nitrogen emissions of each crop production is the sum of on land emissions generated by its corresponding artificial fertilizer, manure, and digestate inputs. On land nitrogen emissions factors are listed in Table 4.

3.5 | Indicators

To answer the first two research questions, we set two indicators: *Nitrogen Fertilizer Replacement Percentage* (NFRP) and *Absolute Consequential Nitrogen Emissions* (Absolute CNE). These indicators are calculated in three concern levels: manure handling, dairy farm, and chain.

- *NFRP* (%) at the two later levels represents how large a percentage of virgin nitrogen artificial fertilizer demand can be replaced by recycling manure or digestate. *NFRP* (%) at manure handling level shows how large a percentage of the nitrogen amount before the handling processes remains in the nutrient recycling flow.

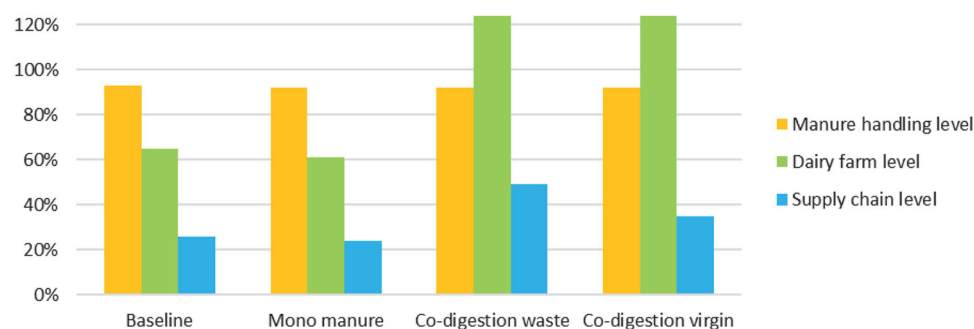
$$\text{NFRP manure handling level} = \frac{N_{\text{manure after storage}} + N_{\text{digestate after storage}}}{N_{\text{manure excreted}} + N_{\text{additional feedstock}}}$$

$$\text{NFRP dairy farm level} = \frac{N_{\text{manure after storage}} \times \text{NFRV}_{\text{manure}} - N_{\text{digestate after storage}} \times \text{NFRV}_{\text{digestate}}}{N_{\text{NDF home feed production}}}$$

$$\text{NFRP supply chain level} = \frac{N_{\text{manure after storage}} \times \text{NFRV}_{\text{manure}} - N_{\text{digestate after storage}} \times \text{NFRV}_{\text{digestate}}}{N_{\text{NDF home feed production}} + N_{\text{NDF cofeed production}} + N_{\text{NDF waste feedstock generation}} + N_{\text{NDF virgin feedstock production}}}$$

TABLE 5 Absolute (consequential) nitrogen emissions in different biogas production options (see Table A4 in Supporting Information S1)

Biogas production options	Manure handling level		Dairy farm level		Supply chain level	
	Absolute N emissions (kgN/year)	Relative to baseline	Absolute N emissions (kgN/year)	Relative to baseline	Absolute N emissions (kgN/year)	Relative to baseline
Baseline	1050	100%	12105	100%	26300	100%
	Absolute CNE (kgN/year)	Relative to baseline	Absolute CNE (kgN/year)	Relative to baseline	Absolute CNE (kgN/year)	Relative to baseline
Mono Manure	+231	22%	+885	7%	+885	3%
Codigestion Waste	+1379	131%	+2744	23%	+2669	10%
Codigestion Virgin	+1379	131%	+2744	23%	+12128	46%

**FIGURE 3** Nitrogen fertilizer replacement percentage of biogas production options at three analytic levels (see Supporting Information S2 for the underlying data)

Comparing this indicator of three anaerobic digestion options with the baseline, we can see the consequential change of biogas production on the nitrogen recycling of current dairy farming practice.

- *Absolute CNE (kgN/year)* indicates the differences of between total nitrogen emissions of each of the production options with biogas output and the baseline. To do this, we must calculate nitrogen emissions of all biogas production options based on processes with emissions identified in the system description (see Section 3.3) and nitrogen emission factors in Table 4. Using this indicator, we can understand the magnitude of consequential nitrogen emission change of biogas production to the current dairy farming practice.

The third question aims to identify the production options with high biogas and less negative change in both nitrogen recycling and emissions. To have a broad overview of the trade-off between making biogas and nitrogen issues, we add two indicators *Biogas output* and *Product-based CNE*, besides *NFRP* and *Absolute CNE*.

- *Biogas output (m³ biogas/year)* for each production options is calculated in Section 3.4.2. Regardless to the analytical level, there is only one biogas output value for each production option.
- *Product-based CNE (kgN/m³ biogas)* is calculated by dividing the absolute CNEs by m³ of biogas produced. This indicator is only calculated for the dairy farm and supply chain level whose stakeholders benefit from making biogas and have responsibility with nitrogen-related issues.

4 | RESULT

The results of our calculation are presented in Table 5 and Figures 3 and 4. Table 5 shows the absolute total nitrogen emissions of the Baseline and the absolute consequential total nitrogen emissions (Absolute CNE) of the three analytic levels. In all options, the CNEs are given as the increase compared to the Baseline. In Figure 3, the nitrogen fertilizer replacement percentage (NFRP) is illustrated and Figure 4 shows the biogas output and Product-based CNE.

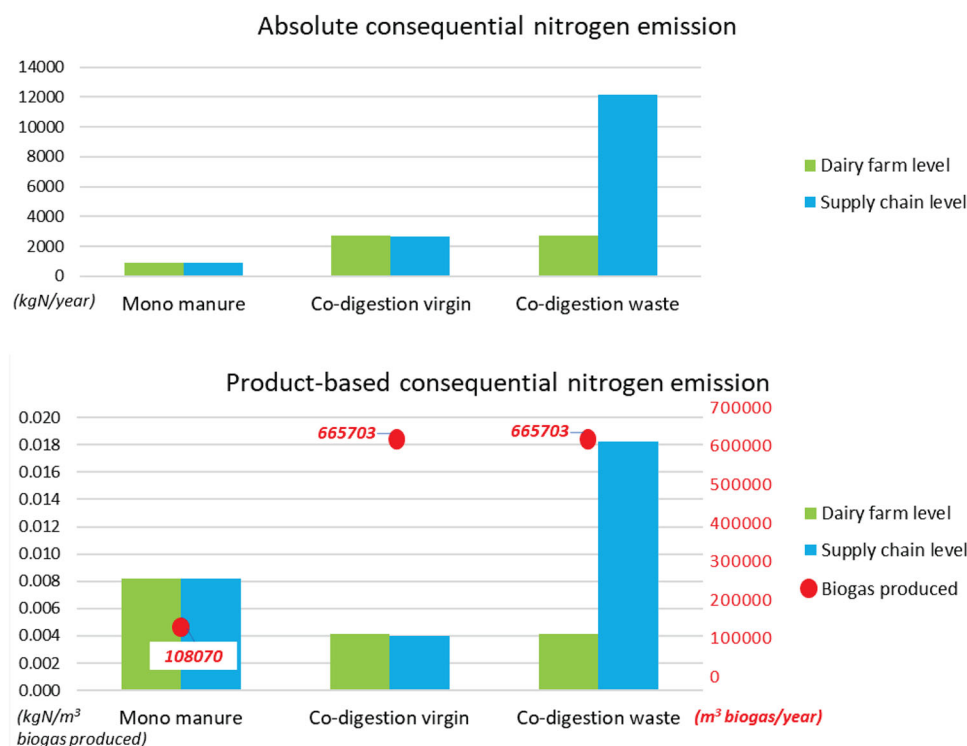


FIGURE 4 Absolute and Product-based consequential nitrogen emissions of biogas production options (see Supporting Information S2 for the underlying data)

4.1 | Absolute consequential changes caused by the biogas production process

4.1.1 | Absolute CNEs of Baseline and Mono Manure

As a direct result of the NH_4 increase, the Mono Manure generates 22% more of gaseous nitrogen emissions than the Baseline. The changing impact of Mono Manure biogas production in dairy farm level and supply chain level are 7% and 3%, respectively (Table 5). This minor change is because the nitrogen emissions from manure handling process itself only accounts for 1/10 to 1/26 of nitrogen emissions of the two larger analytic levels.

4.1.2 | NFRP at manure handling level of all biogas production options

Due to the loss of nitrogen via emissions in manure storage and anaerobic digestion, only a part of nitrogen in manure excreted remains in *manure after storage* and *digestate after storage*. NFRP at manure handling level is 92–93% in all biogas production options. This difference is quite insignificant in comparison with 22% distinction in nitrogen emissions between manure and digestate. The reason is that nitrogen emissions during storage factor of manure and digestate is small, about 6.5–8 kgN emissions per 100 kgN input (Table 4).

4.2 | Absolute consequential changes caused by options of biogas feedstock at manure handling level and dairy farm level

Biogas production from additional feedstock beside manure doubles the Absolute CNE at manure handling level in comparison with the Baseline and the Mono Manure (Table 5). This happens because the amount of nitrogen in additional silage maize is almost the same with the one in manure excreted. At dairy farm level, codigestion cause extra 23% nitrogen emissions (Table 5) which is not as high as at manure handling level. This can be explained by the small contribution of nitrogen emissions at manure handling level to total nitrogen emissions of the dairy farm. Among the forms of nitrogen emissions, NH_3 increases the most with a rise of 20% in Mono Manure and 75% in Codigestion options (Table A4 in Supporting Information S1). Changes in other emissions are around 10% and below.

NFRP of the Baseline and the Mono Manure are 65% and 61%, respectively, while this number in codigestion options are doubled with 124% (Figure 3). The lower number in Mono Manure is because higher nitrogen emissions of digested manure leads to less nitrogen fertilizer replacement capacity. On the other hand, the higher NFRP in codigestion options is the result of the dairy farm receiving additional nitrogen input via the extra biogas feedstock. In this case, the additional nitrogen input via silage maize far surpasses the nitrogen losses due emissions in the form of digested

manure. With *NFRP* at dairy farm level larger than 100%, codigestion options switch the issue on the dairy farm from nitrogen recycling shortage to nitrogen surplus.

There is no difference between Codigestion Waste and Codigestion Virgin options in manure handling level and dairy farm level because their nitrogen flows still look the same in these two analytical levels.

4.3 | Absolute consequential changes caused by options of biogas feedstock at supply chain level

Absolute CNEs at the supply chain level of biogas options have clear divergences (Table 5). While only 10% more nitrogen emissions are caused by digesting additional feedstock from the waste stream, 46% more is caused by virgin additional feedstock. By extending the supply chain system of the biogas production as well as the magnitude of its nitrogen flows, the extra nitrogen emissions from Codigestion Virgin is expected since the system description step. However, the total amount nitrogen emissions go up to almost 1.5 times was not predictable beforehand. This increase in the nitrogen emissions of using a virgin additional feedstock is clearly unignorable. Our calculation shows that the extra nitrogen emissions are not only caused by the difference between manure and digestate but largely because of the nitrogen emissions of artificial fertilizer used for the crop production of the virgin feedstock. The digestate from codigestion options are not enough to return to fulfill the nitrogen demand of the feedstock farm which produces it.

With regard to nitrogen emissions, NH_3 has the greatest increase relative to the baseline (17–59%) as well as the largest share of the total additional emissions (80%) in the case of Mono Manure and Codigestion Waste. In the option of Codigestion Virgin, all types of emissions rise sharply 40–70% in comparison with the baseline; NO_3^- contributes the most to the total extra emissions (75%). This is due to the high NO_3^- emission rate for the additional artificial fertilizer that is required for virgin feedstock production.

The *NFRV* at the supply chain level also show significant differences between biogas production options (Figure 3). *NFRV* at the supply chain level is smaller than *NFRV* at the dairy farm level because the supply chain level regard all farms from the biogas production chain as the applicable receivers of the nutrient recycling flow. Codigestion Waste has the highest *NFRV* (49%) since this is the only option where nitrogen from the existing waste stream is recycled. The difference between the *NFRV* Mono Manure (24%) and Baseline (26%) can also be easily explained by the higher emissions of digestate compared with manure. The *NFRV* of Codigestion Virgin (35%) is a bit higher than the first two options because the large amount of nitrogen input of the codigestion does not go through animal production but only through anaerobic digestion. Animal production has low nitrogen returning percentage (77%, *calculated by dividing nitrogen in feeds to nitrogen in manure*, Table 2) while major nitrogen in feedstock before anaerobic digestion returns after the process (92%, *NFRP at supply chain level of production options with biogas output*).

4.4 | Biogas output and Product-based CNEs

Biogas outputs from Codigestion options are around six times higher than Mono Manure (Figure 4). This confirms the clear different biogas yield potential between manure and silage maize (Table 3).

On the other hand, the calculation of Product-based CNEs provides considerable trade-offs between biogas yield and nitrogen emissions of different biogas production options. At supply chain level, the highest Product-based CNE is from Codigestion Virgin which is twice of the one from Mono Manure and four times of the one from Codigestion Waste. While the relation between the two Codigestion options on Product-based CNE is similar to their one in Absolute CNE indicator, the proportion divergences between Mono Manure and Codigestion options significantly change. With Product-based CNE, Codigestion Waste has half CNEs than Mono Manure. The gap between Mono Manure and Codigestion virgin moves from fifteen times in Absolute CNE to only two times in Product-based CNE.

Product-based CNE at dairy farm level also show the switch between Codigestion and Mono Manure regarding to nitrogen emission impact of biogas production. These extensive changes are resulted from the huge difference in biogas production potential of Mono- and Codigestion which is able to reduce or even cancel out the also-significant difference in nitrogen emissions of those options.

5 | DISCUSSION

In the introduction, we mentioned that the main drivers of making biogas are energy and CH_4 capture while knowing that it also can influence nitrogen issues of the current Dutch dairy farming practice. Our results presented to which extent and on what level different biogas options influence the nitrogen emissions and nitrogen recycling issue. Here we shall discuss the various trade-offs for decision making from different perspectives.

5.1 | Consequences of biogas production at dairy farm level

The dairy farm level is where the biogas production decisions are made and where the legal responsibility of nitrogen are attached. The result discussed in Section 4.1.1 shows that the biogas production process itself barely changes nitrogen emissions and the nitrogen recycling capacity in

comparison with the baseline. Thus, from an environmental perspective, Mono Manure is a good practice for capturing a type of greenhouse gas emission (CH_4) while interfering less with nitrogen issues of the current Dutch dairy farming. However, this solution for capturing CH_4 comes with relatively little biogas production.

To obtain higher biogas output, codigestion options are more interesting options, but they also cause nitrogen emissions to increase (Table 5) and make the problem of nitrogen recycling more serious (Figure 3), especially with silage maize. From an environmental perspective, this is an evident trade-off for making energy and reducing the climate change impact of CH_4 . The surplus nitrogen must be moved elsewhere to avoid a greater environmental problem which generally costs money. Together with the cost of purchasing additional feedstock, the profit of codigestion is still debatable (Agostini et al., 2016; Hoppe, Ph, & Sanders, 2014). Though we do not include an economic analysis in this study, the link between material flows and economic considerations clearly cause a dilemma. This raises the questions whether biogas production is beneficial or burdensome for dairy farmers from both an environmental and economic point of view.

By using SFA at the dairy farm level, we can see that nitrogen emissions are only critical at the farm level in the codigestion cases but not Mono Manure. While nitrogen emissions mostly have a local impact, LCA studies aggregate emissions from the whole product system. This results in every type of biogas production leading to increase nitrogen emissions, despite major differences at the dairy farm level. On the other hand, since a certain amount of nitrogen always leaves the production system in the form of dairy products and emissions, the nitrogen surplus issue has not been addressed at the supply chain level included in LCAs. Through SFA this impact is revealed. These implications show that assessing biogas production system at multiple levels with SFA can contribute to fill the research gaps identified in the introduction.

5.2 | Consequences of biogas production at supply chain level

Our results also show that codigestion increases nitrogen flows of the total system and thus emissions at the supply chain system. NO_3^- , which causes eutrophication, constitutes most of the additional emissions for Codigestion Virgin compared to Mono Manure. Although values in this case study differ from previous research, they are still within the same magnitude (Paolini et al., 2018; Pehme et al., 2017)

Besides, we can relate the result at the supply chain level to the national context. First, we can see that when biogas is promoted on dairy farms, nitrogen emissions will increase both for dairy farming and crop production. Secondly, if a particular quantity of biogas is expected to be produced, then Codigestion Waste leads to the least increase in nitrogen emissions in comparison with the baseline based on the Product-based CNE indicator. Alternatively, Mono Manure leads to double the amount of extra emissions compared to the Codigestion Waste case, and the Codigestion Virgin case is four times as large (Figure 4). However, having lower nitrogen emissions at the national scale by codigesting waste will still increase local nitrogen emissions for farmers. Since the two main forms of extra emissions, NH_3 and NO_3^- , have environmental impact at local level, this increase in numbers also increases direct local environmental damage such as odor nuisance, air pollution, health problems, and eutrophication.

5.3 | Is Codigestion Waste always the “best” option?

Based on the supply chain level results, Codigestion Waste appears to be the option of making energy with the least negative trade-off in nitrogen issues. In the case of Codigestion Waste, biogas production can also contribute to nitrogen recycling. If digestate from the codigestion is allowed to be distributed to farms surrounding the dairy farms, then even the nitrogen surplus issue at the dairy farm level can be easily solved.

However, in practice, not all nitrogen from waste streams is desired by farmers. Plant-based waste such as garden waste and industrial processed vegetable can be contaminated with unwanted substances that end up in digestate and make it no longer suitable as fertilizer. In such a case, the nitrogen recycling capacity of the Codigestion Waste is almost zero.

Another issue with waste streams is that it is limited (Table 3). While virgin feedstock has clear drivers to be cultivated, the existence of waste is avoided. With the current trends of recycling and circular economy, waste streams are not only limited in amount but also in accessibility because of other competing uses.

Last but not least, in this paper, the waste has a clear win because it hypothetically has the same biogas yield with silage maize—a quite high biogas yield feedstock. In fact, waste feedstock might not have that high biogas yield, and high biogas yield by-products are not often considered as waste. In theory, Codigestion Waste is an attractive biogas production decision, but in practice, only a few options may be available for building a strong biogas economy on dairy farm from waste.

5.4 | Contribution of feedstock selection to mediating the energy–nitrogen trade-offs

The results of nitrogen emissions, nitrogen recycling, and the trade-offs in different levels are strongly correlated with the nitrogen content and biogas yield of the feedstock, as well as the codigestion ratio.

Silage maize is the most common option now and via the model built in this paper we can see the potential nitrogen impacts and trade-offs of our current biogas production practice. However, by playing with this model and looking at characteristics of other available biogas feedstocks, each

farmer or each location can build up the best options for sustainable biogas production. On the other hand, empirical studies on introducing the new type of biogas feedstock can also use this model to predict the large-scale impacts of their recommendations with regard to nitrogen issues.

Based on the modelling approach developed in this paper, biogas researchers, and practitioners can customize their own high-yielded biogas production systems with less negative change in nitrogen issues or predict the nitrogen impacts based on the inputs of the biogas production options.

5.5 | Limitations

The goal of our research is to identify the magnitude of nitrogen change between different biogas production options and different levels of system analysis. However, to further develop this framework for forecasting and estimation purposes, the following needs to be taken into account:

- *The dynamic of nitrogen flows*: nitrogen flows are sensitive to the seasonal variations, temperatures, and soil conditions. For example, the timing of planting and fertilizers application can influence the speed of nitrogen mineralization, nitrogen uptakes and different forms of nitrogen emissions. These could lead to the changes in the total nitrogen emissions and recycling capacity in all levels.
- *Farm management styles*: Culture, economy, and local regulation can be the reason for the variation in farm management styles. Farms can vary in sizes, production levels, production mixtures, etc. These can affect the amount of imported feed, home-grown feed, and amount of land that manure can be recycled. This can cause the significant changes in the indicators at the farm level as well as its relations with the two other analytical levels.
- *Influence of biogas codigestion on the cropping practice*: in most cases, the virgin feedstock farm is not newly created for biogas production. The feedstock from for biogas product could have been used for other purposes or come from farms with land use changes. To have a local evaluation of the impact of biogas production options on the current farming practice, these alternatives use of feedstock and land uses should be considered. There might be a case of no increase in nitrogen emission of the location, but with the supply chain perspective, once virgin feedstock is used, biogas production will always cause extra emission somewhere else to compensate for the alternative uses of the feedstock.

6 | CONCLUSION

This study points out significant trade-offs between biogas production and nitrogen problems. It also suggests assessing energy production systems by SFA approach at multiple levels to reveal such trade-offs. Mono-digestion of manure does not significantly affect nitrogen issues of the current Dutch dairy farming practice, but its biogas output is low. Codigestion options, in the cases of silage maize and hypothetical waste feedstock with similar characteristics, can considerably increase biogas output but will also increase the nitrogen problems. At the dairy farm level, codigestion options lead to 23% higher emissions and lead to nitrogen surplus issue. At the supply chain level, codigesting virgin feedstock increases 1.5 times of nitrogen emissions. Using waste feedstock only adds 10% extra nitrogen emissions and highly increases the nitrogen recycling capacity of the whole agricultural system of the biogas production chain. In national context, Codigestion Waste is the production choice which theoretically helps extract more biogas with less nitrogen issue trade-offs; however, options of waste feedstock for biogas can be limited in practice. The awareness of these trade-offs and limitations can support practitioners to make decisions related to future biogas production.

To conclude, the present global emissions of reactive nitrogen are considered a threat to global sustainability (Erisman et al., 2013). This paper shows that production of biogas comes with extra nitrogen emissions and local nitrogen surplus issue. These consequences should be taken into consideration. Otherwise, measures to reduce climate change, are threatening the globe in other environmental themes.

ACKNOWLEDGMENTS

This study is done as a part of ADAPNER project—Adaptive Logistics in Circular Economy, under the sponsorship of NWO, grant 428-15-519 of TKI-Logistiek. NWO (Nederlandse Organisatie voor Wetenschappelijk Onderzoek) is the Dutch Organisation for Scientific Research. The objective of ADAPNER project is to study and select viable configurations of value-adding activities related to biomass and biogas in a Circular Economy.

CONFLICT OF INTEREST

The authors have no conflict to declare.

ORCID

Dieu Linh Hoang  <https://orcid.org/0000-0002-5768-068X>

REFERENCES

- Afrane, G., & Ntiamoah, A. (2011). Comparative life cycle assessment of charcoal, biogas, and liquefied petroleum gas as cooking fuels in Ghana. *Journal of Industrial Ecology*, 15(4), 539–549.
- Agostini, A., Battini, F., Padella, M., Giuntoli, J., Baxter, D., Marelli, L., & Amaducci, S. (2016). Biomass and bioenergy economics of GHG emissions mitigation via biogas production from sorghum, maize and dairy farm manure digestion in the Po valley. *Biomass and Bioenergy*, 89, 58–66. <https://doi.org/10.1016/j.biombioe.2016.02.022>
- Air Pollution Information System. (2016). *Nitrogen deposition*. Retrieved from UK Air Pollution Information System website: http://www.apis.ac.uk/overview/pollutants/overview_N_deposition.htm
- Alberola, C., Lichtfouse, E., Navarrete, M., Debaeke, P., & Souchère, V. (2008). Agronomy for sustainable development. *Italian Journal of Agronomy*, 3(3), 77–78.
- Bacenetti, J., Sala, C., Fusi, A., & Fiala, M. (2016). Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable. *Applied Energy*, 179, 669–686. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0306261916309709>
- Blonk Consultant. (2012). *LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization: GHG emissions of N, P and K fertilizer production* (pp. 1–15). Gauda, The Netherlands: Author.
- BOKU & KTBL. (2010). *Online European feedstock atlas*. Retrieved from <https://daten.ktbl.de/euagrobiogasbasis/startSeite.do;jsessionid=667A3DFA67F7B6267AB74FE9806FA71A>
- Bonten, L. T. C., Zwart, K. B., Rietra, R. P. J. J., Postma, R., & de Haas, M. J. G. (2014). Bio-slurry as fertilizer; Is bio-slurry from household digesters a better fertilizer than manure? A literature review. Wageningen, Alterra Wageningen UR (University & Research centre), Alterra report 2519..
- Brunner, P. H., & Rechberger, H. (2011). *Practical handbook of material flow analysis* (pp. 5–13). Boca Raton, FL: Lewis Publishers. Retrieved from <http://link.inghub.elsevier.com/retrieve/pii/B9781856178099100039>
- Burton, C. H., & Turner, C. (2003). *Manure management: Treatment strategies for sustainable agriculture* (2nd ed.). Bedford, UK: Silsoe Research Institute.
- CCBT. (2013). *Biologische champost ter beschikking!* Retrieved from <http://www.ccbt.be/?q=node/303>
- Centraal Veevoederbureau. (2016). *Tabellenboek veevoeding 2016* (CVB-reeks nr. 53). Federatie Nederlandse Diervoederketen.
- Chatzimpiros, P., & Barles, S. (2013). Nitrogen food-print: N use related to meat and dairy consumption in France. *Biogeosciences*, 10(1), 471–481.
- Daatselaar, C. H., Reijers, J. R., Oenema, J., Doornwaard, G. J., & Aarts, H. F. M. (2015). Variation in nitrogen use efficiencies on Dutch dairy farms. *Journal of the Science of Food and Agriculture*, 95(15), 3055–3058.
- de Boer, H. C. (2017). *Nitrate leaching from liquid cattle manure compared to synthetic fertilizer applied to grassland or silage maize in the Netherlands* (pp. 1–32). Retrieved from <http://edepot.wur.nl/425920>
- Deublein, D., & Seteinhauser, A. (2008). *Biogas from waste and renewable resources*. Weinheim, Germany: Wiley-VCH.
- de Vries, J. W., Vinken, T. M. W. J., Hamelin, L., & de Boer, I. J. M. (2012). Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy—A life cycle perspective. *Bioresource Technology*, 125, 239–248. <https://doi.org/10.1016/j.biortech.2012.08.124>
- Dumont, M. (2012). *Biogas situation in the Netherlands*. Task 37. IEA-Bioenergy.
- Erisman, J. W., Galloway, J. N., Seitzinger, S., Bleeker, A., Dise, N. B., Petrescu, A. M. R., ... de Vries, W. (2013). Consequences of human modification of the global nitrogen cycle. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1621), 20130116.
- European Fertilizer Manufacturers' Association. (2000a). *Best available techniques for pollution prevention and control in the European fertilizer industry*. Booklet No. 1 of 8: Production of ammonia. Brussels, Belgium: Author.
- European Fertilizer Manufacturers' Association. (2000b). *Best available techniques for pollution prevention and control in the European fertilizer industry*. Booklet No. 6 of 8: Production of ammonium nitrate and calcium ammonium nitrate. Brussels, Belgium: Author.
- Fields, S. (2004). Global nitrogen: Cycling out of control. *Environmental Health Perspectives*, 112(10), 556–563.
- Gebrezgabher, S. A., Meuwissen, M. P. M., & Oude Lansink, A. G. J. M. (2010). Costs of producing biogas at dairy farms in the Netherlands. *International Journal Food System Dynamics*, 1, 26–35. Retrieved from <https://ageconsearch.umn.edu/bitstream/91139/2/3-Meuwissen-OAJ.pdf>
- Hijazi, O., Munro, S., Zerhusen, B., & Effenberger, M. (2016). Review of life cycle assessment for biogas production in Europe. *Renewable and Sustainable Energy Reviews*, 54, 1291–1300. <https://doi.org/10.1016/j.rser.2015.10.013>
- Hoppe, T., Ph, M., & Sanders, T. (2014). Agricultural green gas demonstration projects in the Netherlands. *A Stakeholder Analysis*, 13(12), 3083–3096.
- Intergovernmental Panel on Climate Change. (2006). N₂O emissions from managed soils, and CO₂ emissions from lime and urea application. In S. Eggleston, L. Buendia, K. Miwa, T. Ngara, & K. Tanabe (Eds.), *IPCC guidelines for national greenhouse gas inventories*, Vol. 4: Agriculture, Forestry and Other Land Use (pp. 1–54). Hayama, Japan: Institute for Global Environmental Strategies.
- Kamphus, M. (2014). Emission monitoring in nitric acid plants. *Nitrogen+Syngas*, 328(2), 48–53. Retrieved from http://www2.emersonprocess.com/siteadmin/center/PMRosemountAnalyticalDocuments/PGA_PUB_201404_NS-328_Emission_Monitoring_in_Nitric_Acid_Plants.pdf
- Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S., ... Westhoek, H. J. (2015). Impacts of European livestock production: Nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. *Environmental Research Letters*, 10(11), 115004.
- Lukehurst, C., Frost, P., & Al Seadi, T. (2010). Utilisation of digestate from biogas plants as biofertiliser. IEA Bioenergy. Retrieved from <http://www.biogas.org.nz/Publications/Resources/utilisation-of-digestate-biogas-to-biofertiliser.pdf>
- Meliksetian, V. (2018). *The Netherlands can't afford to keep its natural gas promise*. OilPrice.com. Retrieved from <https://oilprice.com/Energy/Natural-Gas/The-Netherlands-Cant-Afford-To-Keep-Its-Natural-Gas-Promise.html>
- Möller, K., Schulz, R., & Müller, T. (2010). Substrate inputs, nutrient flows and nitrogen loss of two centralized biogas plants in southern Germany. *Nutrient Cycling in Agroecosystems*, 87(2), 307–325.
- Ohyama, T. (2010). Nitrogen as a major essential element of plants. In T. Ohyama, & K. Sueyoshi (Eds.), *Nitrogen assimilation in plants* (pp. 1–17). Thiruvananthapuram, India: Research Signpost.

- Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., & Cecinato, A. (2018). Environmental impact of biogas: A short review of current knowledge. *Journal of Environmental Science and Health, Part A*, 53(10), 899–906. <https://doi.org/10.1080/10934529.2018.1459076>.
- Pehme, S., Veromann, E., & Hamelin, L. (2017). Environmental performance of manure co-digestion with natural and cultivated grass—A consequential life cycle assessment. *Journal of Cleaner Production*, 162, 1135–1143. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0959652617312374>
- Pratt, P. F., & Castellanos, J. Z. (1981). Available nitrogen from animal manures. *California Agriculture*, 35(7), 24.
- Quik, J. T. K., Mesman, M., & van der Grinten, E. (2016). *Assessing sustainability of residual biomass applications: Finding the optimal solution for a circular economy*. RIVM rapport 2016-0135.
- Ramírez-Arpide, F. R., Demirel, G. N., Gallegos-Vázquez, C., Hernández-Eugenio, G., Santoyo-Cortés, V. H., & Espinosa-Solares, T. (2018). Life cycle assessment of biogas production through anaerobic co-digestion of nopal cladodes and dairy cow manure. *Journal of Cleaner Production*, 172, 2313–2322. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0959652617328536>
- Rosenberg, L., & Kornelius, G. (2017). Experimental investigation of biogas production from feedlot cattle manure. *Journal of Energy in Southern Africa*, 28(4), 1–8. Retrieved from <http://www.scielo.org.za/pdf/jesa/v28n4/01.pdf>
- RVO. (2018a). *Stikstof gebruiksnorm en gebruiksruimte*. Retrieved from <https://www.rvo.nl/onderwerpen/agrarisch-ondernemen/mest-en-grond/gebruiks-ruimte-berekenen/stikstofgebruiksnorm-en-ruimte>
- RVO. (2018b). *Standard excretion factors per dairy cow 2018*. Retrieved from <https://www.rvo.nl/sites/default/files/2015/04/Tabel6-versie2015-2017-versie-januari2015.pdf>
- RVO. (2018c). *Biomass SDE+*. Retrieved from <https://www.rvo.nl/subsidies-regelingen/stimulering-duurzame-energieproductie/categorieën/biomassa-sde>
- Schröder, J. J. (2000). Koei'n 1.0: stroomdiagram en balans voor stikstof op melkveehouderijbedrijven: rekenblad ontwikkeld in het kader van het derogatieverzoek van EU-nitraatrichtlijn. (Nota / Plant Research International; No. 37). Wageningen: Plant Research International.
- Schröder, J. J. (2009). *Simulated nutrient management options for intensive livestock farms with a surplus of manure*. Paper presented at Eurofert 09, L'Europe de La Fertilisation, Rennes, France, February 3–4, 2009.
- Schröder, J. J., & Neeteson, J. J. (2008). Nutrient management regulations in the Netherlands. *Geoderma*, 144(3–4), 418–425.
- Sims, J. T., & Maguire, R. O. (2005). Manure management. In *Encyclopedia of soils in the environment* (pp. 402–410). Retrieved from <https://www.sciencedirect.com/science/article/pii/B0123485304005154>
- Sørensen, P., & Møller, H. B. (2011). Nitrogen fertilizer value of digestates from anaerobic digestion of animal manures and crops. *NJF Seminar No. 443*, pp. 14–15.
- Stucki, M., Jungbluth, N., & Leuenberger, M. (2011). *Life cycle assessment of biogas production from different substrates*. ESU-Services Ltd.
- Tiwary, A., Williams, I. D., Pant, D. C., & Kishore, V. V. N. (2015). Emerging perspectives on environmental burden minimisation initiatives from anaerobic digestion technologies for community scale biomass valorisation. *Renewable and Sustainable Energy Reviews*, 42, 883–901. Retrieved from <https://www.sciencedirect.com/science/article/pii/S1364032114008776>
- Tufaner, F., & Aşar, Y. (2016). Effects of co-substrate on biogas production from cattle manure: A review. *International Journal of Environmental Science and Technology*, 13(9), 2303–2312.
- van der Voet, E. (2002). Substance flow analysis. In R. U. Ayres, & L. W. Ayres (Eds.), *A handbook of industrial ecology* (pp. 91–101). Cheltenham, UK: Edward Elgar.
- Van Grinsven, H. J. M., Tiktak, A., & Rougoor, C. W. (2016). Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. *NJAS - Wageningen Journal of Life Sciences*, 78, 69–84. <https://doi.org/10.1016/j.njas.2016.03.010>.
- van Middelaar, C. (2014). *Milk production and greenhouse gases*. Wageningen University & Research.
- Velten, E. K., Donat, L., Andrew, E., Prah, A., & Wevers, M. (2014). *Assessment of climate change policies in the context of the European Semester Country Report*. The Netherlands.
- Velthof, G. L., van Bruggen, C., Groenestein, C. M., de Haan, B. J., Hoogeveen, M. W., & Huijsmans, J. F. M. (2012). A model for inventory of ammonia emissions from agriculture in the Netherlands. *Atmospheric Environment*, 46, 248–255. <https://doi.org/10.1016/j.atmosenv.2011.09.075>.
- Vonk, J., Bannink, A., van Bruggen, C., Groenestein, C. M., Huijsmans, J. F. M., van der Kolk, J. W. H., ... Velthof, G. L. (2016). Methodology for estimating emissions from agriculture in the Netherlands. Retrieved from <http://library.wur.nl/WebQuery/wurpubs/504907>
- Wageningen University & Research. (2018). *Dutch dairy farms—Holding structure*. BINternet – Agro and Food Portal. Retrieved from <https://www.agrimatie.nl/Binternet.aspx?ID=3&Bedrijfstype=2&SelectedJaren=2017@2016@2015@2014&GroteKlassen=Allebedrijven>
- Webb, J., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., ... Reid, J. (2010). *Study on variation of manure N efficiency throughout Europe*. Retrieved from http://ec.europa.eu/environment/water/water-nitrates/pdf/Man_N_Eff_FinalReport.pdf
- Wierzbowska, J., Sienkiewicz, S., Krzebietke, S., & Sternik, P. (2016). Sewage sludge as source of nitrogen and phosphorus for Virginia fanpetals. *Bulgarian Journal of Agricultural Science*, 22(5), 722–727.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Hoang DL, Davis C, Moll HC, Nonhebel S. Impacts of biogas production on nitrogen flows on Dutch dairy system: Multiple level assessment of nitrogen indicators within the biogas production chain. *J Ind Ecol*. 2020;24:665–680. <https://doi.org/10.1111/jiec.12956>